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Assessment of Landscape Risks and Ecological Security Patterns in the Tarim Basin, Xinjiang, China

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Abstract: Ecological risk refers to the potential threat that landscape changes pose to ecosystem structure, function, and service sustainability, while ecological security emphasizes the ability of regional ecosystems to maintain stability and support human well-being. Developing an Ecological Security Pattern (ESP) provides a strategic approach to balance ecological protection and sustainable development. This study investigates the spatial and temporal dynamics of landscape ecological risk in the Tarim Basin and surrounding urban areas in the Xinjiang Uygur Autonomous Region, China, from 2000 to 2020. Using a combination of the InVEST model, landscape connectivity index, and circuit theory-based modeling, we identify ecological source areas and simulate ecological corridors. Ecological source areas are categorized by their ecological value and connectivity: primary sources represent high ecological value and strong connectivity, secondary sources have moderate ecological significance, and tertiary sources are of relatively lower priority but still vital for regional integrity. The results show a temporal trend of ecological risk declining between 2000 and 2010, followed by a moderate increase from 2010 to 2020. High-risk zones are concentrated in the central Tarim Basin, reflecting intensified land-use pressures and weak ecological resilience. The delineated ecological protection zones include 61,702.9 km^2 of primary, 146,802.5 km^2 of secondary, and 36,141.2 km^2 of tertiary ecological source areas. In total, 95 ecological corridors (23 primary, 37 secondaries, and 35 tertiary) were identified, along with 48 pinch points and 56 barrier points that require priority attention for ecological restoration. Valuable areas refer to those with high ecological connectivity and service provision potential, while vulnerable areas are characterized by high ecological risk and landscape fragmentation. This study provides a comprehensive framework for constructing ESPs in arid inland basins and offers practical insights for ecological planning in desert–oasis environments.

Keywords: ecological security model; remote sensing; the InVEST model; oasis–desert transition zone

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1. Introduction

Ecological issues such as pollution, climate change, and environmental degradation pose significant challenges to human habitation and sustainable development [1,2]. These alterations significantly jeopardize the health and sustainable advancement of human societies, resulting in a multitude of ecological issues, including vegetation degradation [3], water scarcity [4], soil erosion [5,6], habitat fragmentation [7], and loss of biodiversity [8]. The stability of ecosystems is significantly impacted [9]. Currently, ecological security has

emerged as a pivotal and essential objective of national sustainable development programs. The Biodiversity Strategy for 2030 aims to safeguard a minimum of 30 percent of the Earth's terrestrial, marine, and freshwater ecosystems by the year 2030. The augmentation of conservation strategy aims signifies an expansion in the breadth of conservation efforts [10]. Consequently, developing ecological security patterns (ESPs) that optimize resource allocation, protect ecosystem services, and improve environmental resilience has become a priority in ecological research [11,12].

Ecological risk denotes the hazards faced by ecosystems and their constituents, illustrating the adverse effects of environmental alterations and human societal actions on ecosystems. Landscape ecological risk (LER) refers to the likelihood of detrimental ecological effects resulting from alterations in landscapes and habitats, impacting biodiversity, ecosystems, and their normal functioning [13,14]. Research on landscape environmental risk assessment originated in the 1990s and, after decades of development, has evolved into a prominent field of study within ecology and geography [15]. The findings are of significant practical importance for developing ecological risk mitigation strategies and optimizing the allocation of limited resources. Research suggests that landscape ecological risk assessment (LERA) provides valuable insights into the spatial distribution of ecological risks caused by external disturbances [16]. This may evaluate the spatial distribution of potential detrimental ecological effects on landscapes subjected to diverse threats. Moreover, it is often utilized to guide the formulation of ecological conservation strategies within a region [17]. The Ecological Security Pattern (ESP) is essential for preserving the structural and functional integrity of ecosystems. The theory of landscape ecology underpins this approach, simulating ecological landscape change trends by analyzing spatial locations and interconnections among various landscapes, thereby offering theoretical support and detailed implementation strategies for safeguarding regional ecological security [18]. Landscape-scale spatial planning, adopting a holistic perspective, integrates ecological conservation and restoration efforts with sustainable development initiatives [19]. ESPs alleviate habitat fragmentation and environmental degradation by establishing ecological sources, resistance surfaces, and corridors [20,21].

The ecological safety model is primarily implemented through a comprehensive ecological network that encompasses (1) identification of ecological sources, (2) development of an integrated resistance surface, (3) extraction of ecological corridors, and (4) formulation of the security model [11,22]. In ecological source area documentation, the focus is on specifically identifying regions capable of delivering substantial ecosystem services and significantly contributing to regional ecological security [23]. Initial research regarded ecosystems, ecological reserves, or extensive woodlands as ecological sources [24]. This method, which primarily identifies sources based on the current state, is often highly subjective, fails to adequately consider the importance of ecological sources in ecological processes and functions, and tends to neglect regions with potential ecological services during ecological restoration [25]. The InVEST model is extensively employed to calculate services provided by ecosystems. It accurately and efficiently evaluates habitat quality across several scales and can assist in finding ecological sources. Confrontation surfaces are employed to measure the facilitation of species movement through spatial contexts. Both natural and artificial resistance components are typically regarded when designing a comprehensive structure. Recently, researchers have integrated topographical elements, nocturnal illumination data, and ecological danger indices to improve resistant surfaces depending on regional variables, thereby augmenting the objectivity and scientific rigor of ecological resistance models [26]. Circuit theory further enhances connectivity modeling by simulating species movement probabilistically, helping to locate ecological pinch points and barriers more accurately than traditional least-cost path models [27–29]. However, many

ESP construction methods lack applicability in ecologically vulnerable and heterogeneous regions such as mountainous desert oases. This study addresses that gap by proposing a suitable ESP framework for the Tarim Basin in Xinjiang.

The Tarim Basin is a large arid inland area in Central Asia, marked by a mountain–oasis–desert ecosystem. It is highly sensitive to climate change and anthropogenic pressures, including rapid urbanization and unsustainable agricultural expansion. Over 95% of water resources are consumed by agriculture [30], and desertification and habitat fragmentation continue to worsen [31]. Artificial oases and intensive cropping systems have further reduced ecological security [32]. Despite its ecological significance, research on ESPs for this region remains limited and unvalidated. Consequently, to effectively address climate change and human-induced environmental degradation in the Tarim Basin of Xinjiang, it is essential to investigate its ecological risks, establish an ecological security model, and formulate a pragmatic plan for regulating ecological safety in the area.

This study integrates landscape ecological risk assessment and ecological network modeling to address these gaps. The objectives are as follows: (1) to examine the spatial and temporal patterns of landscape ecological risks in the Tarim Basin; (2) to analyze the spatial configuration of ecological networks and identify key influencing factors; and (3) to propose conservation priorities and optimization strategies for enhancing ecological security in the oasis–desert context of Xinjiang.

2. Materials and Methods

2.1. Study Area of Tarim Basin

Located in southern Xinjiang, the Tarim Basin is China's largest inland basin, covering a vast area with elevations ranging from 567 to 5569 m and featuring a terrain that slopes from west to east (Figure 1). It lies within the Xinjiang Uygur Autonomous Region, a historically significant area that once served as a major corridor on the ancient Silk Road and now plays a key role in the second "Asia–Europe Continental Bridge". This strategic location underscores the region's geopolitical and economic importance. Xinjiang's terrain is composed of 56% mountainous areas and 44% basins. The Tarim Basin is dominated by desert and Gobi landscapes, with a typical arid continental climate. Annual precipitation ranges between 50 and 100 mm, while the average annual temperature is about 8.63 °C. Vegetation is sparse, mainly consisting of salt- and drought-tolerant shrubs and herbaceous plants, forming unique plateau–oasis–desert ecosystems. According to data from the Xinjiang Statistical Yearbook (2025), the population of the Tarim Basin Economic Circle reached 11.95 million in 2025, accounting for 46.2% of Xinjiang's total population. The region's GDP stood at 482 billion yuan, making up 30.1% of the regional total. The Tarim Basin is also rich in natural resources, including petroleum, natural gas, and various minerals, reinforcing its status as one of China's key energy bases. However, rapid urbanization and human interference have disrupted ecological processes, threatening regional ecological security. To promote sustainable development, it is imperative to implement ecological restoration and conservation strategies. These efforts are crucial for future land-use planning and the long-term ecological stability of the Tarim Basin.

2.2. Data Sources

This study utilizes land-use data from 2000 to 2020, along with digital elevation models, normalized difference vegetation index (NDVI), and road and water supply system data from 2023 for the Tarim Basin in Xinjiang. The land-use types are classified into six major categories: cultivated land, forest land, grassland, water bodies, built-up land, and unused land. The land-use data and NDVI were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn, accessed

on 15 January 2025). Digital elevation, slope, and topographic data were sourced from the Geospatial Data Cloud platform (https://www.gscloud.cn, accessed on 15 January 2025), while road and hydrological data were acquired from OpenStreetMap (http://www.openstreetmap.org/, accessed on 15 January 2025). All data were normalized to 30 m resolution using the projected coordinate system WGS_1984_UTM_Zone_48N.

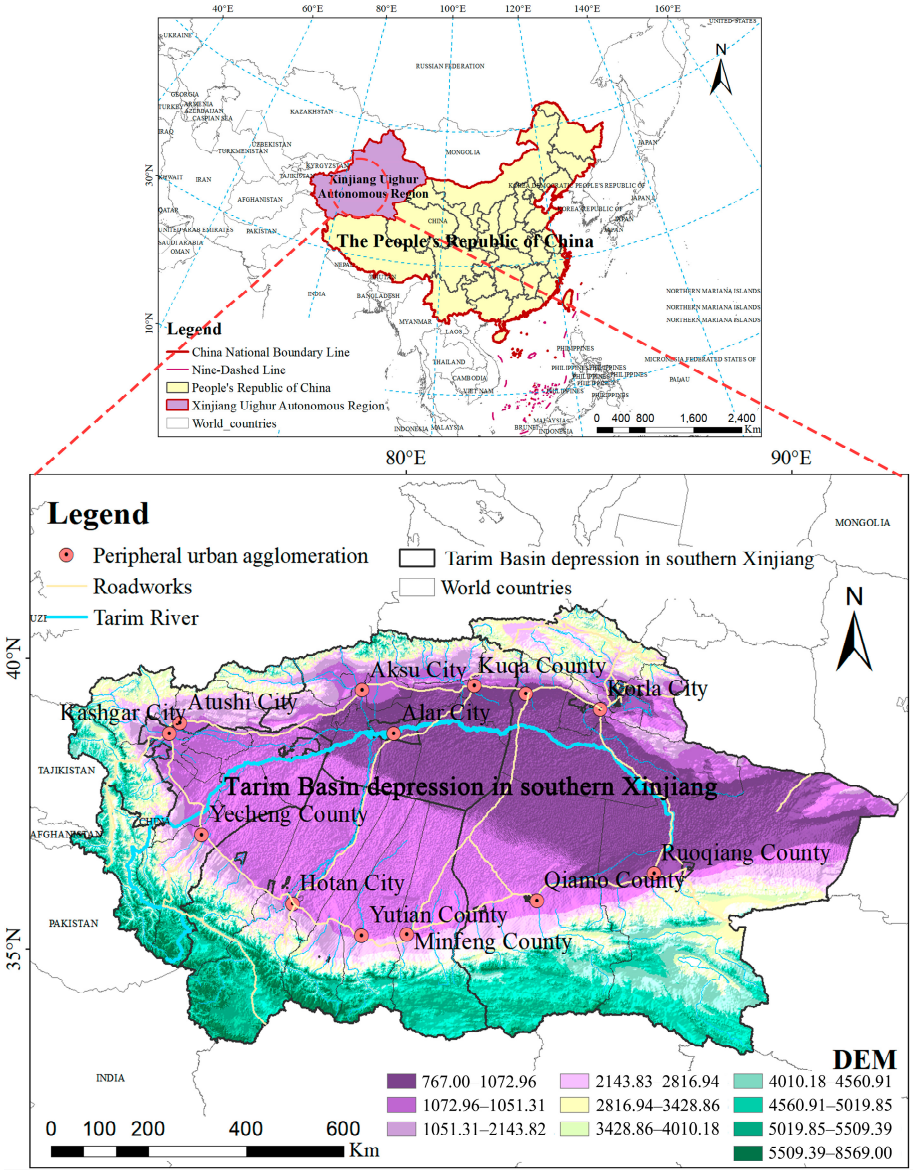


Figure 1. Locations of Xinjiang Uighur Autonomous Region in China.

2.3. Methodology

The ecological security pattern of the Tarim Basin and its surrounding urban agglomerations in Xinjiang was comprehensively determined in this study by integrating landscape ecological risk analysis, habitat quality assessment, landscape connectivity evaluation, and circuit theory. Initially, the spatial and temporal evolution of landscape ecological risks was analyzed using land-use data from 2000, 2010, and 2020. Subsequently, the regional ecological system construction was developed and refined through a systematic procedure, encompassing the identification and classification of ecological sources, the construction of integrated resistance surfaces, the extraction of ecological corridors, and the identification of key nodes [11]. Ultimately, by integrating the findings of the landscape ecological risk assessment with the characteristics of the ecological network structure, the research region

was ecologically zoned, and specific ecological protection techniques were recommended. Figure 2 illustrates the theoretical research framework.

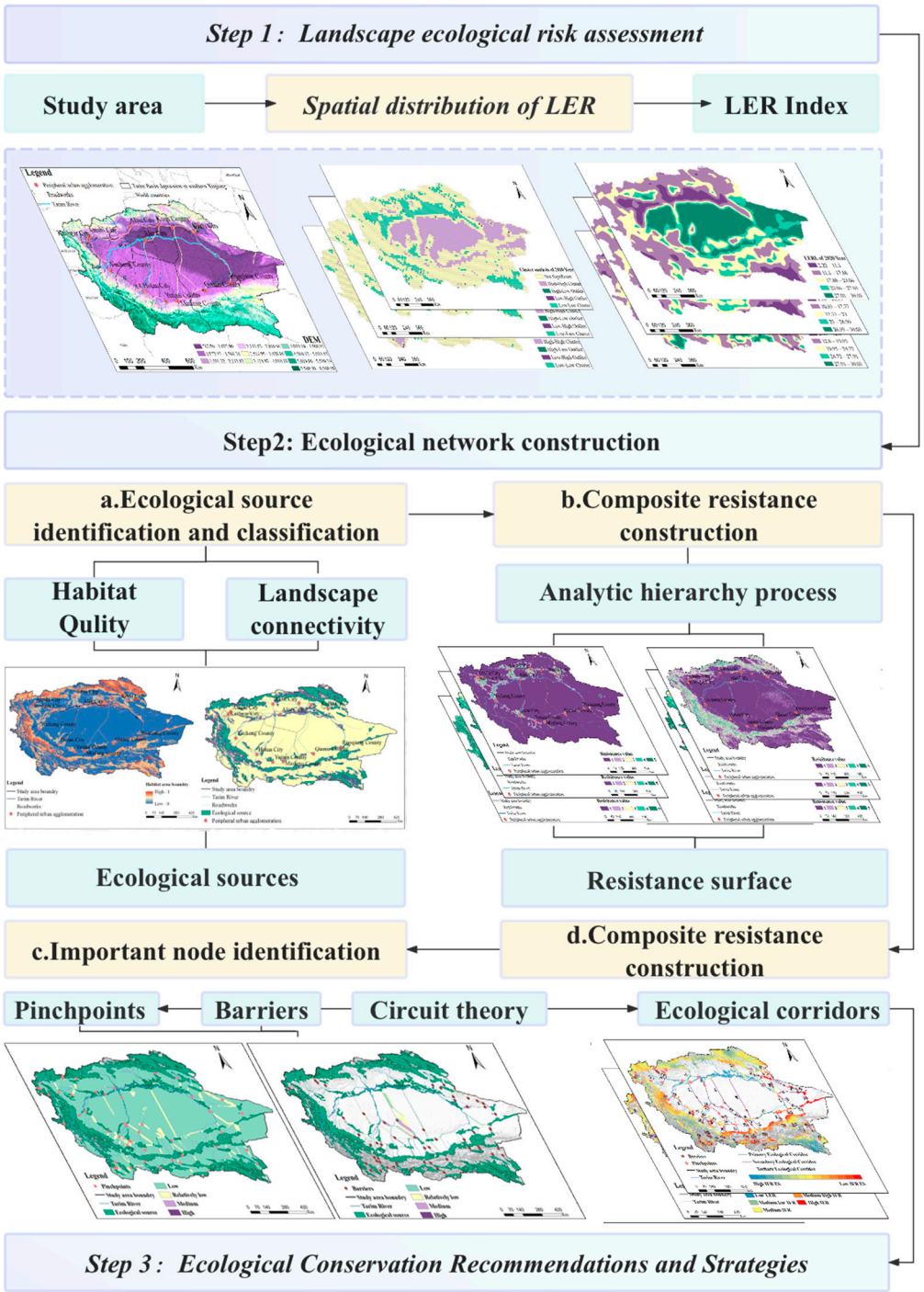


Figure 2. Methodological flowchart used for the current study.

2.3.1. Ecological Risk Assessment of Landscapes

The index of landscape pattern is extensively utilized in evaluating landscape ecological risk due to its notable efficacy in statistically assessing and characterizing spatial variability [30]. This research thoroughly investigated the geographical and chronological development of landscape ecological danger in the Tarim Basin, employing land-use data from 2000, 2010, and 2020. The ecological risk of the landscape was determined by the landscape disruption index and the landscape sensitivity index. The landscape disturbance index measures the severity of natural and human-induced disturbances, usually com-

puted as a weighted amalgamation of the environment fragmentation index, environment separation index, and environment dimensionality index [33]. Relevant research indicate that the weights of the three indices are established as a = 0.5, b = 0.3, and c = 0.2, respectively [17]. The landscape vulnerability index was subsequently employed to evaluate the stability of terrain types. The landscape types of the Tarim Basin were classified into six categories—arable land, woodland, grassland, water, building land, and unoccupied land—by synthesizing earlier research with the current situations of the research area, and the landscape vulnerability index was calculated through normalization. Table 1 delineates the exact formulas and definitions of the corresponding indices.

Table 1. Formula for calculation and importance of the IER value.

Name	Formula		Meaning
Landscape Fragmentation Index (C_i)	$C_i = \frac{n_i}{A_i}$	(1)	The intricacy of the spatial arrangement of the landscape in response to exogenous disturbances.
Landscape Separation Index (N_i)	$N_i = \frac{1}{2} \times \sqrt{\frac{n_i}{A_i}} \times \frac{A}{A_i}$	(2)	Spatial heterogeneity of a certain terrain patch.
Landscape Rational Dimension Index (F_i)	$F_i = 2ln(p_i/4)/lnA_i$	(3)	The intricacy of landscape typologies within the research area.
Landscape Disturbance Index (E_i)	$E_i = aC_i + bN_i + cF_i$	(4)	Indicates the degree to which particular landscape units are affected by external disturbances.
Landscape Vulnerability Index (Q_i)	Derived on geographical facts and expert evaluations, and standardized		Vulnerability of the landscape to external disruptions.
Landscape Loss Degree Index (R_i)	$R_i = E_i \times Q_i$	(5)	Natural deterioration of the terrain resulting from external interference.
Landscape Ecological Risk Index (IER_i)	$IER_i = \sum_{i=1}^{n} \frac{A_{ij}}{A_i} \times R_i$	(6)	Mirroring alterations in the ecological milieu

2.3.2. Identification and Classification of Ecological Sources

(1) Identification of ecological sources:

Ecological source areas are crucial for ecological processes, serving as patches that sustain ecological integrity and deliver high-quality services [34]. The quality of habitat might indicate the ecological appropriateness of an ecosystem [35]. This study employed the model to statistically evaluate the ecological source sites in the Tarim Basin, identifying crops, urbanized land, and unused land as the primary issues impeding ecological security. The formula for computation is presented in Table 2.

Table 2. The sensitivity of land-use type to threat factors.

Land Type	Weights	Maximum Impact Distance (km)	Attenuation Function	Habitat Suitability	Sensitivity to Stressors		
					Cultivated Land	Constructed Land	Unutilized Land
Cultivated land	0.5	4	Linear	0.4	0	0.4	0
Woodland	-	-	-	0.7	0.3	0.6	0.3
Grassland	-	-	-	0.8	0.4	0.5	0.1
Waters	-	-	-	0.9	0.6	0.9	0.4
Constructed land	1	8	Exponential	0	0	0	0
Unutilized land	0.2	2	Linear	0.1	0.2	0.3	0

(2) Ecological source classification:

Examining the influence of natural resources on landscape connectivity might elucidate how conservation zones should be prioritized. Landscape connectedness assists as a

crucial metric for evaluating types migration between ecological sources and its effects on ecosystem stability and biodiversity conservation [36]. The graph theory-based connectivity integration index (IIC) and the probability of connectivity (PC) serve to quantify the overall connectivity of a landscape and the relative significance of specific ecological patches to that connectivity. To evaluate the significance of landscape aspects more thoroughly, it is necessary to introduce connectivity integral index (dIIC) and connectivity probability (dPC) criteria to quantify the impacts of specific landscape components. To integrate the functions of these two indices, the equal weighted values of dIIC and dPC were employed as the comprehensive assessment index in this study. Landscape connectedness was studied across several distance threshold conditions to ascertain the connection pattern under the ideal distance threshold. The computation method and definitions of associated variables are detailed in Table 3.

Table 3. Formulations and meaning of habitat value and landscape connectivity.

Classification	Formulations	Meaning
Habitat quality Calculation	$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{rmax}}\right)$ (7) $i_{rxy} = exp\left(-\left(\frac{2.99}{d_{rmax}}\right)d_{xy}\right)$ (8)	In this context, i_{rxy} represents the influence of threat r at grid y on the habitat grid at position x, d_{xy} signifies the linear distance between grids x and y, and drmax specifies the greatest distance over which threat r exerts its effect.
	$D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\omega_r / \sum_{r=1}^{R}\omega_r\right) r_y i_{rxy} \beta_x S_{jr}$ (9)	In this equation, D_{xj} represents the overall threat level of grid x in habitat j, y encompasses all grids on the raster map of threat r, Y_r denotes the grids situated within a grid cell on the raster map of threat r, i_{rxy} signifies the impact of the threat on grid y within the habitats at location x, β_x indicates the accessibility level of the grid, and S_{jr} reflects the sensitivity of land use and land cover to threat r, ranging from 0 to 1, with values approaching 1 indicating greater sensitivity.
	$Q_{xj} = H_j\left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right]$ (10)	This constitutes the equation for assessing habitat quality. Q_{xj} represents the habitat quality of grid x in habitat type j, D_{xj} denotes the level of disturbance experienced by grid x in habitat type j, and k is the half-saturation constant, often established at 0.05. H_j denotes the habitat appropriateness for habitat type j. Z is the regularization constant, established at 2.5.
Landscape connectivity Calculation	$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \times a_j}{1+nl_{ij}}}{A_L^2}$ (11) $dIIC(\%) = \frac{IIC - IIC_{remove}}{IIC} \cdot 100$ (12) $PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij}^* \times a_i \times a_j}{A_L^2}$ (13) $dPC(\%) = \frac{PC - PC_{remove}}{PC} \cdot 100$ (14)	In this equation, n represents the total number of patches, a_i and a_j represent the areas of blocks i and j, respectively, nl_{ij} indicates the landscape connectivity between i and j, A_L symbolizes the total area, and P_{ij}^* reflects the optimality of direct organism dispersal between i and j. $dIIC$ and dPC represent the significance of the patches; a larger value indicates greater importance to the overall landscape connectivity.

2.3.3. Structure of a Comprehensive Resistance Surface

The ecological resistance surface illustrates the impact of landscape variability on ecological processes, with the value representing the extent of barriers to species mobility and the transfer of material information within an ecosystem. Generally, enhanced environmental functioning correlates with a reduction in migration resistance, whereas an increase in resistance yields the contrary effect [37]. This study selected a resistance factor that incorporates both natural and manmade influences, based on the sparse vegetation characteristics and significant alterations in topography and geomorphology within the study area. Six primary resistance elements were identified, founded on pertinent investigations and the existing circumstances of cities surrounding the Tarim Basin [38]. The resistance factor weights were initially established by the AHP, followed by the creation of the integrated ecological confrontation surface utilizing ArcGIS software 10.8 (Table 4).

Table 4. Resistance surface factors and their weighting factors.

Factor	Resistance Measurement					Weight
	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5	
Elevation	<500 m	500–1000 m	1000–1500 m	1500–3000 m	>3000 m	0.2378
Slope	<5°	5°–15°	15°–25°	25°–35°	>35°	0.1523
Vegetation cover	>55%	30–55%	15–30%	5–15%	<5%	0.2067
Land type	Forest land	Waters and grassland	Agricultural	Bare	Construction land	0.4563
Distance to river	<500 m	500–1000 m	1000–2000 m	2000–5000 m	>5000 m	0.0457
Distance to construction land	<500m	500–1000 m	1000–2000 m	2000–5000 m	>5000 m	0.0234

2.3.4. Extraction of Ecological Corridors

Biological corridors are essential components for sustaining biological processes and ensuring landscape connection. This study identifies ecological corridors utilizing circuit theory through Linkage Mapper (Linkage Path Tool). This technique delineates and charts the most economical routes between ecological source locations by combining an ecological source vector map with a combined confrontation surface raster map [39]. In a resistance surface raster, each raster cell is assigned a value that signifies the energy consumption, migratory challenge, or risk of death linked to traversing the cell. As organisms disperse from a particular ecological origin, a cost-weighted length assessment generates an aggregate motion impedance map that illustrates connectedness between neighboring ecological source sites, thereby identifying the least expensive ecological corridor between these sources.

2.3.5. Identification of Critical Nodes

Ecological pinch points are critical zones of elevated animal activity that enhance habitat accessibility and mitigate overall ecological risk in the area [40]. This research utilized the Pinchpoint Mapper software 3.0 to identify ecological pinch points through circuit theory. The core principle asserts that each ecological strip linking near ecological source sites operates as a conduction surface, while the ecological source sites are regarded as nodes within the circuit. A current of 1A is provided at each node through a grounding operation, enabling the calculation of the total current value at each pixel to evaluate the significance of ecological source sites and corridors, ultimately identifying the distribution of potential pathways and bottlenecks.

Ecological barriers significantly impede animal movement, making their identification and elimination crucial for improving ecological corridor connectivity. This study employed the Barrier Mapping tool to assess the ecological barriers within the study area. The program uses the moving window technique to detect areas that may impede ecological processes and evaluates the impact of these barriers on landscape connection by calculating recovered connection standards per unit distance [11].

3. Results

3.1. Landscape Ecological Risk Distribution

Figure 3 illustrates the spatiotemporal dynamics of landscape ecological risk (LER) in the Tarim Basin over three representative years: 2000, 2010, and 2020, thereby capturing its periodic characteristics. Figure 3a displays the LER spatial distribution maps, highlighting a persistent pattern characterized by low risk in core oasis zones and higher risk in peripheral desert–oasis transition areas. Over time, high-risk zones exhibit a gradual outward expansion, particularly along ecotonal fringes, suggesting the progressive intensification of ecological stress. This trend reflects the periodic accumulation of landscape risk in response

to increasing human disturbance and land-use change. Figure 3b shows the results of LISA (Local Indicators of Spatial Association) cluster analysis. The identification of statistically significant High–High and Low–Low clusters across the three periods confirms the spatial dependence of LER. The temporal shifts in cluster patterns—especially the expansion of high-risk clusters—indicate dynamic hotspots of ecological vulnerability and provide insight into the spatially continuous and periodic evolution of landscape risk. Figure 3c presents scatter plots and fitted curves illustrating the relationship between LER and a key driving variable. The increasing R^2 values from 2000 (0.668) to 2010 and 2020 (both 0.744) suggest an enhanced explanatory power of the driver over time, implying that the impact of anthropogenic or ecological factors on LER has become more pronounced. This reinforces the notion of temporally accumulated risk. Collectively, these subfigures capture the periodic nature of ecological risk from both spatial and statistical perspectives, offering a comprehensive understanding of landscape risk evolution in arid inland basins.

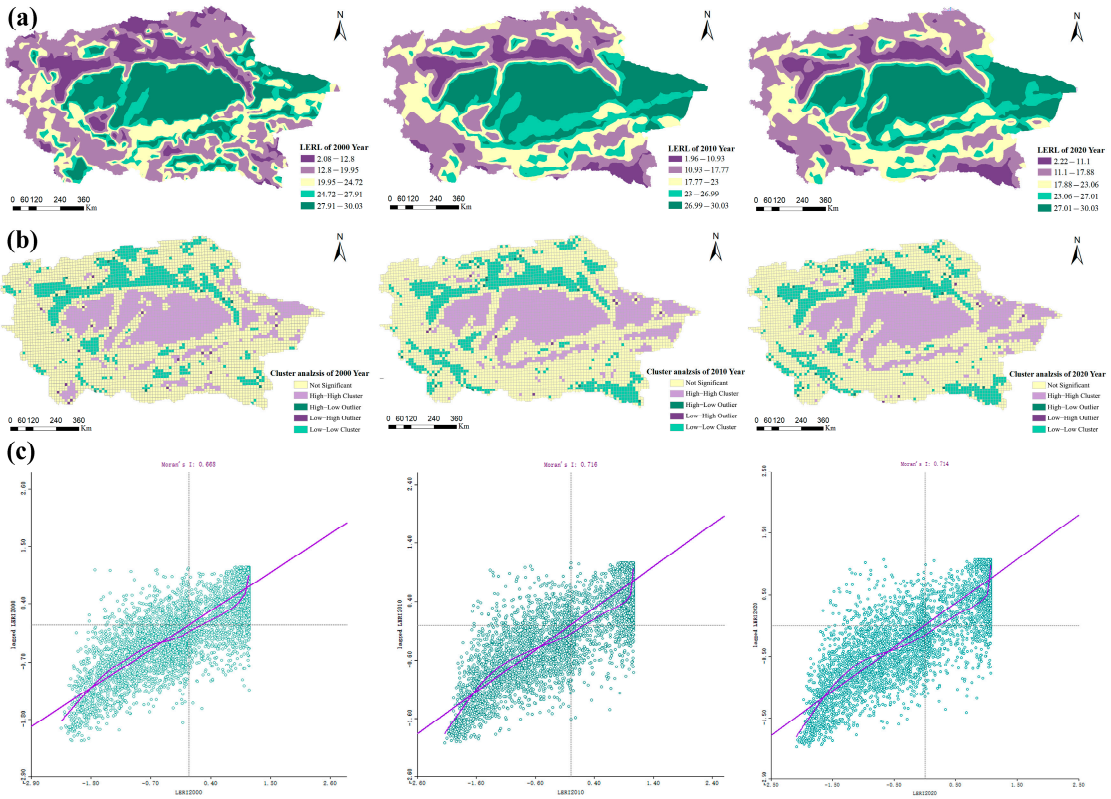


Figure 3. IER distribution (**a**), IER cluster (**b**), IER global Moran's index (**c**), 2000–2020.

3.2. Identification of Ecological Sources

This research systematically examined the regional distribution of habitat quality in the Tarim Basin with a habitat quality rating model. The findings indicated that the overall habitat quality in the study region was commendably high, with the regions of superior habitat quality predominantly located in the mountainous and oasis zones bordering the Tarim Basin (Figure 4a). The study examined 42 biological source patches including a total area of 244,646.6 km^2, primarily consisting of woodland, grassland, and aquatic environments (Figure 4b). The ecological source patches were subsequently classified according to the landscape connectedness index. The ecological source patches were branded into three classes founded on the ranking outcomes of the composite landscape connectivity index: patches 33 and 35 were designated as primary ecological sources, patches 2, 3, 9, 10, 13, 14, 19, 30, 32, and 43 were classified as secondary ecological sources, while the remaining 31 patches (1, 4–8, 11–12, 15–29, 31, 34, 36–42) were identified as tertiary ecological foun-

dations. Tier 1 ecological sources are mainly situated in the highland hilly region of the southern Tarim Basin, including an area of 61,702.9 km^2, and are distinguished by their aggregation in extensive singular patches. Secondary ecological sources predominantly occupy the southern oasis and northern highlands, with a total area of 146,802.5 km^2, which exceeds that of the primary and tertiary ecological sources. Tertiary ecological sources are dispersed and exhibit tiny patch sizes, encompassing an entire area of 36,141.2 km^2 (Figure 5).

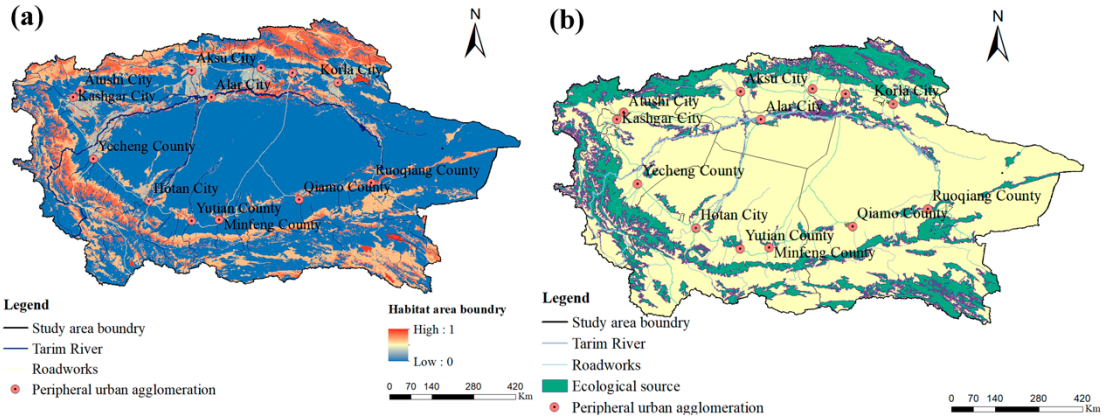


Figure 4. Habitat quality distribution (**a**) and ecological source site identification (**b**).

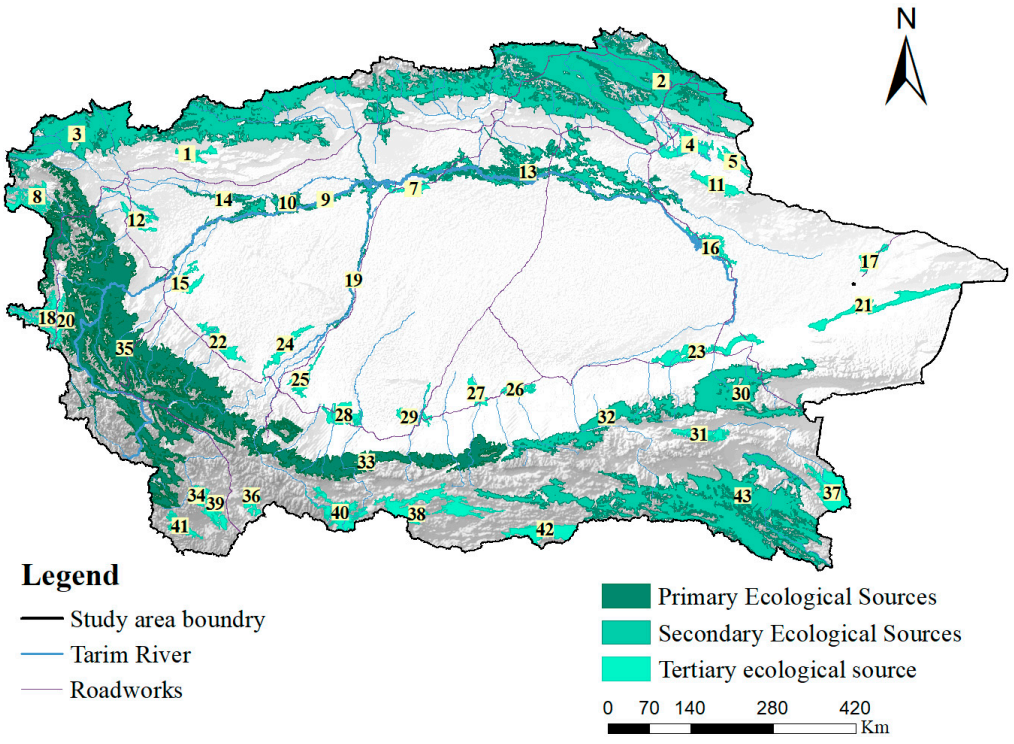


Figure 5. Ecological source classification.

3.3. Comprehensive Resistance Surface Construction Distribution

This study quantitatively evaluated six barrier factors: elevation, slope, land type, vegetation cover, proximity to major rivers, and proximity to build land, to create a comprehensive ecological resistance surface in the study area (Figure 6). The findings designated that the combined confrontation values in the studied area varied from 1.15 to 5.0, demonstrating significant spatial variation. The regions exhibiting elevated resistance values were predominantly located in densely urbanized areas and the arid desert region in the

center part of the country, characterized by intricate topography and a degraded natural environment. Conversely, regions of poor resilience are prevalent in oasis and mountainous locations, characterized by desert oasis ecosystems, exhibiting excellent habitat quality and ecological connection (Figure 7).

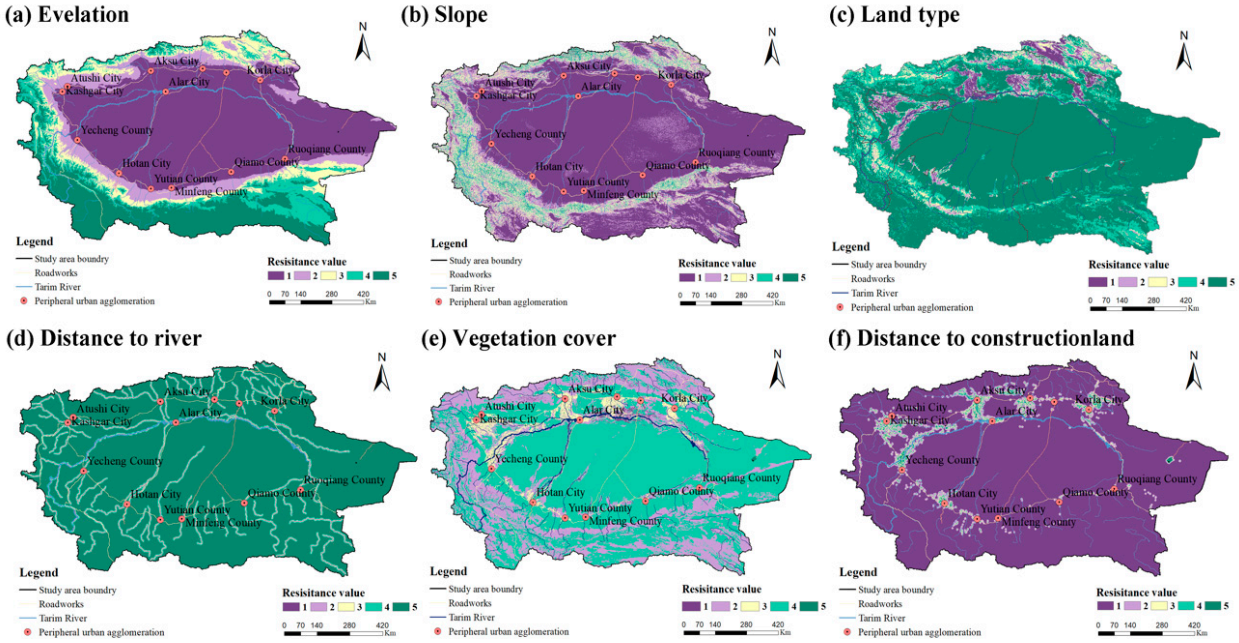


Figure 6. Distribution of resistance factor values.

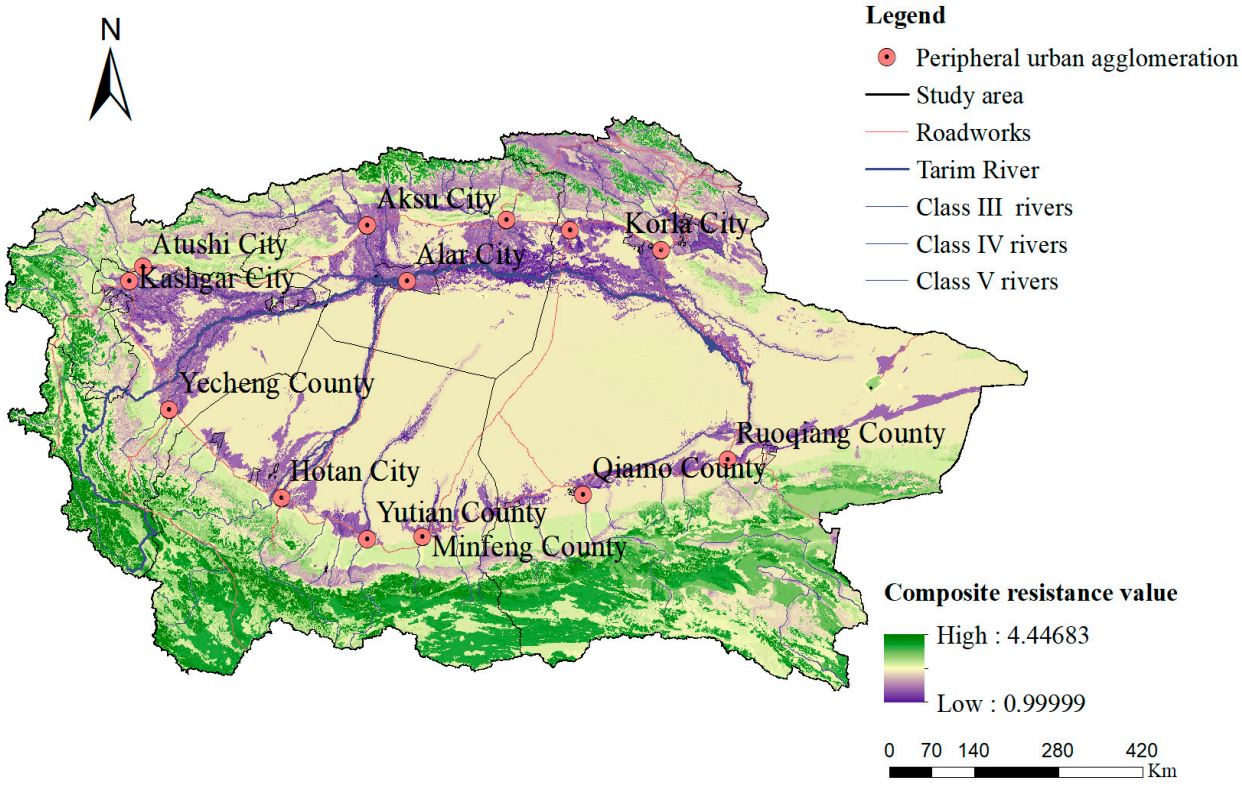


Figure 7. Ecological resistance surfaces in Tarim Basin depression in southern Xinjiang.

3.4. Identification of Corridors and Important Node

The investigation of circuit philosophy revealed 95 essential ecological corridors in the Tarim Basin, creating a reticulated ecological framework with a cumulative length of 56,265.5 km. The study's findings indicate that adequate corridor width significantly contributes to the improvement of ecological functions within ecological corridors. In conjunction with prior research, the breadth of the ecological strips was established to exceed 600 m to accommodate the migratory requirements of large and medium-sized mammals, thereby ensuring the survival and migratory needs of various species. The distribution of ecological corridors exhibits important spatial variation, characterized by a high density of multiple short corridors in the eastern region, hence facilitating short-distance species migration. The ecological corridors in the west are extensive, linking the southern Tianshan Mountains Water Conservation Ecological Zone, the Pamir-Kunlun Mountains Water Conservation and Biodiversity Conservation Zone, and the Pamir-Kunlun Mountains Soil and Water Erosion Protection Zone with the Tianshan Water Conservation Ecological Zone in the northern Aksu region and the Bayinbuluk National Nature Reserve in Bazhou.

The study's findings indicate that corridors 37, 38, 39, 47, 48, 49, 50, 51, 52, 65, 67, 68, 69, 70, 71, 72, 76, 77, 78, 79, 82, 83, and 88 are designated as Level 1 ecological corridors; corridors 17, 26, 27, 28, 29, 30, 32, 33, 35, 36, 40, 41, 42, 43, 44, 45, 46, 53, 54, 55, 56, 57, 58, 62, 63, 64, 66, 73, 74, 75, 80, 81, 89, 91, 92, 93, and 94 are classified as Level II ecological corridors; whereas corridors 1 to 25, 31, 34, 59, 60, 61, 84, 85, 86, 87, 90, and 95 are identified as tertiary ecological corridors.

Key ecological nodes were dispersed across the study area, with ecological pinch points primarily situated at the junction of ecological sources and corridors, whereas ecological barrier points were predominantly found between corridors. Subsequent investigations revealed that the ecological pinch points were predominantly situated in regions with substantial plant cover and in proximity to water systems (Figure 8), which are vital for sustaining ecological connections. The ecological barriers were predominantly situated in the southern region, characterized by elevated topography, sparse plant cover, and proximity to urban fringes, hence significantly jeopardizing the connection of the ecological corridors. A total of 48 pinch spots and 56 obstacles were discovered, serving as a fundamental basis for improving the regional ecological network.

3.5. The Correlation Between Landscape Ecological Risk and Ecological Resources

The study revealed that Tier 1 ecological sources are predominantly located in regions with elevated Landscape Ecological Risk Index (LERI), whereas Tier 2 and Tier 3 ecological sources are primarily found in areas with low LERI, as demonstrated in Figure 9. The biological source areas in the research region primarily consisted of woods and desert oasis. Nevertheless, the escalation of desertification and landscape fragmentation in recent years may elucidate why larger ecological source areas typically demonstrate elevated ecological risk. The study's results indicate that these high-quality habitats exhibit greater sensitivity to external disturbances, notwithstanding their significant ecological importance. Consequently, stringent conservation actions must be enacted for high-grade ecological source areas that exhibit elevated ecological hazards to bolster the stability and sustainability of their ecological functions (Figure 10).

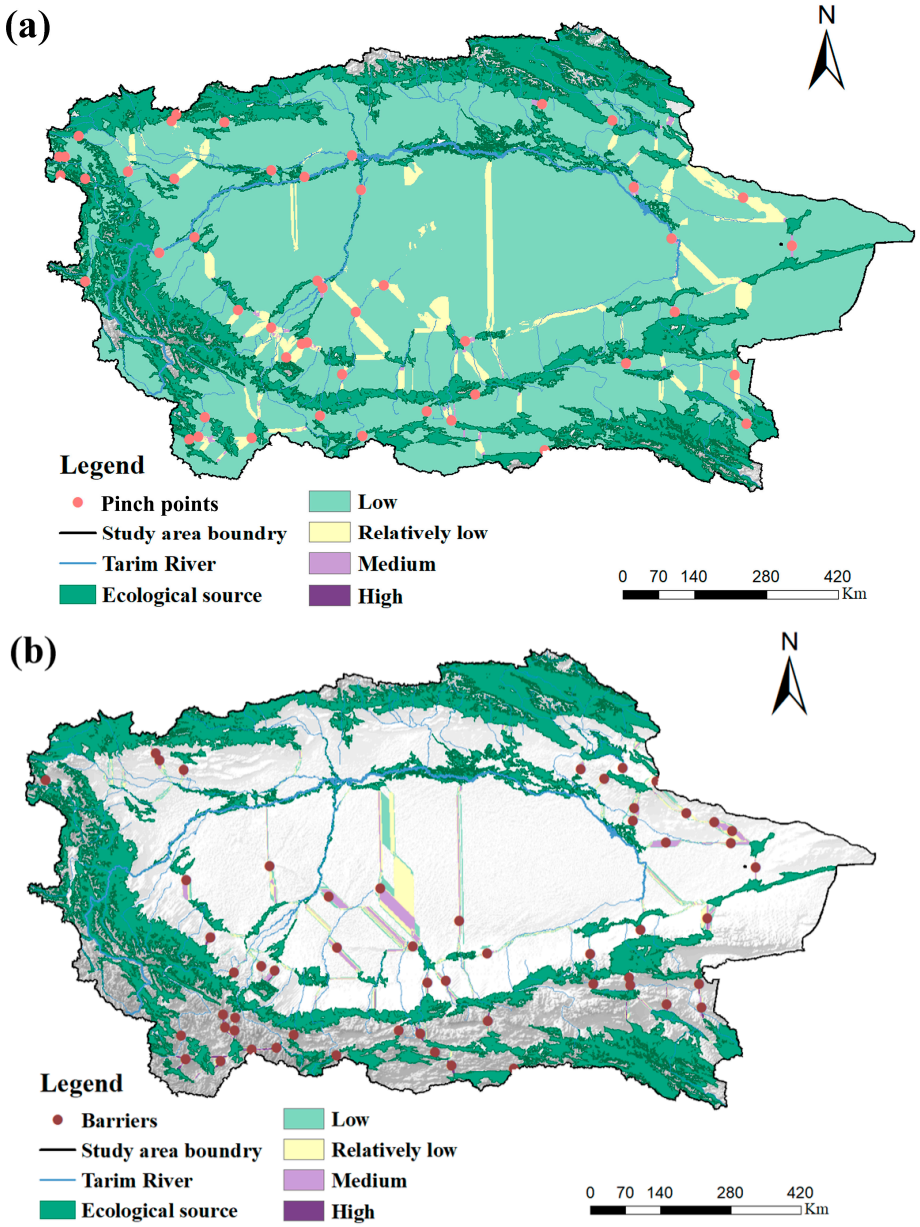


Figure 8. Ecological pinch points (**a**) and ecological barriers (**b**).

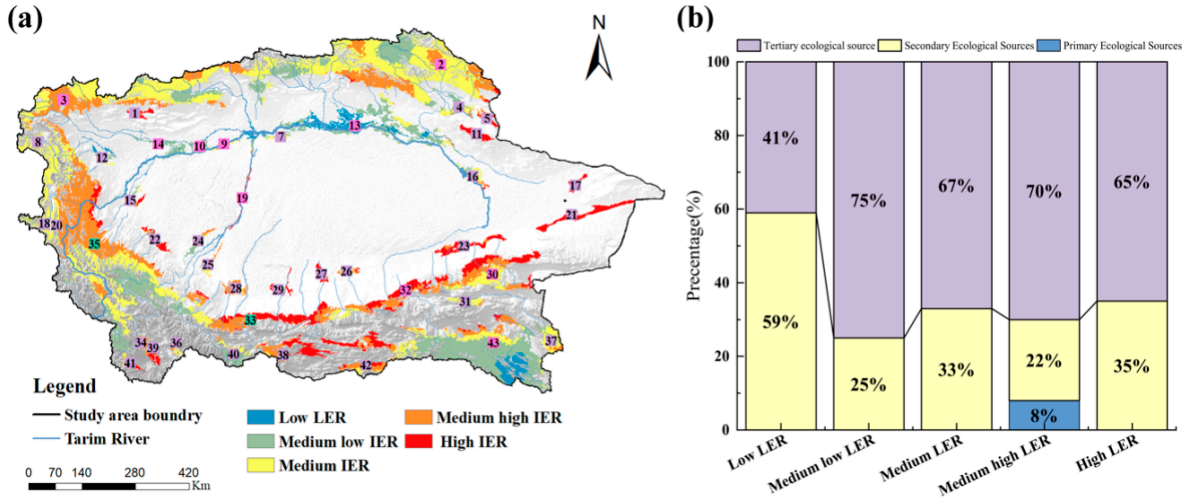


Figure 9. Ecological risk in ecological source landscapes (**a**) and the distribution (**b**).

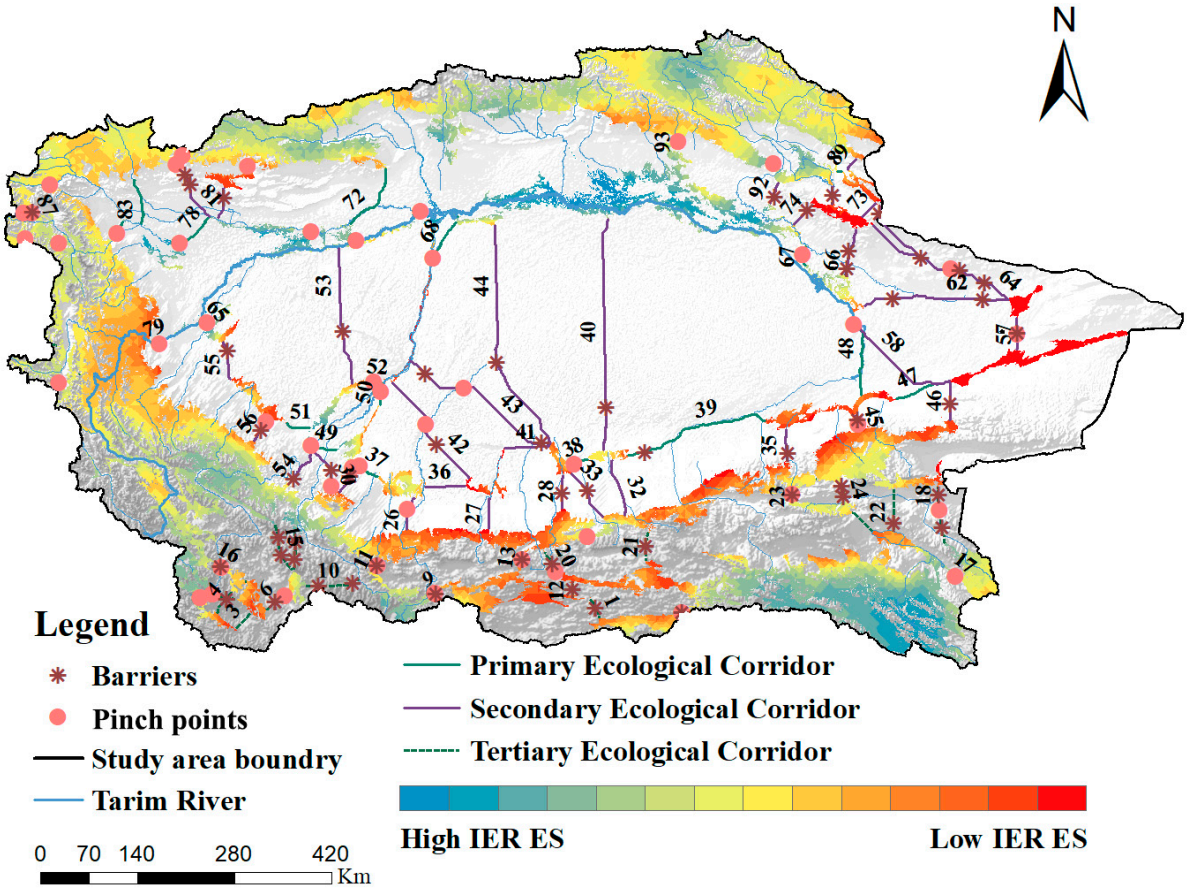


Figure 10. Classification of ecological corridors and their pinch points and obstacle points.

4. Discussion

4.1. Identification of Corridors and Important Nodes: Assessment of Landscape Ecological Risk and Identification of Ecological Network

This study integrates LER and landscape connectivity, employing circuit theory to delineate the spatial scope of ecological corridors and identify critical nodes, thereby providing a novel approach to constructing an ESP for the Tarim Basin in Xinjiang. In addressing ecological issues such as weak water conservation and severe soil erosion in oasis areas, resistance surface factors were evaluated and classified. The study utilized MSPA and patch importance indices to identify ecological sources. MSPA simplifies the assessment of landscape patterns, making changes more intuitive and providing a new foundation for landscape pattern analysis [41,42]. Additionally, this research quantitatively evaluates the connectivity of core patches, reducing the subjectivity involved in manually selecting ecological sources in previous studies [43]. By integrating current ecological conditions with the region's ecological demands, the method minimizes subjective interference. The combination of ecological source distribution, risk assessment, and connectivity analysis forms a solid basis for determining conservation and restoration priorities [44].

The study identifies buffer zones around ecological networks—areas with low-intensity land use—as critical for ecosystem service provision. These zones serve as ecological shields, mitigating disturbances from urban development and acting as transitions between natural and socio-economic systems. They provide ecosystem services essential to human well-being. By applying circuit theory, the study simulates animal migration patterns based on random walk principles, highlighting ecological pinch points as key to improving landscape connectivity [45]. Recognizing ecological barriers emphasizes the need to address the negative effects of human activity hotspots [46]. The integration of

LER evaluation into ESP construction provides a solid foundation for developing regional conservation strategies, particularly suited to arid desert–oasis regions [47].

4.2. Recommendations and Strategies for the Protection of Ecological Security Patterns

This study delineates a spatially explicit ecological security pattern (ESP) for the oasis regions surrounding the Tarim Basin, emphasizing the importance of regionally adaptive conservation strategies in arid inland areas. The results indicate that ecological connectivity between the northern and southern subregions remains relatively weak, and ecologically sensitive areas—particularly those near urban and agricultural expansion fronts—are highly vulnerable to anthropogenic disturbances. These findings are consistent with previous studies in arid river basins, such as the Heihe and Shule River Basins, which report similar patterns of ecological fragmentation and increased landscape risk in urban–agricultural transition zones [48,49]. However, our work extends this understanding by integrating fine-scale connectivity analysis with ecological risk gradients, offering a more spatially nuanced diagnosis of ecological vulnerability. To address these risks, we recommend implementing China's "Three Zones and Three Lines" policy—ecological redlines, permanent basic farmland, and urban development boundaries—as a foundational zoning mechanism. Similar zoning frameworks have demonstrated positive ecological outcomes in the Yangtze River Economic Belt and the Loess Plateau [50], where clear functional demarcations reduced land-use conflicts and promoted targeted ecological restoration. Our findings suggest that applying this strategy to the Tarim Basin, with local adjustments based on risk and connectivity mapping, can significantly enhance ecological resilience while accommodating development pressures.

Building on this policy foundation, we propose a novel "Two Shields, One Ring, Multiple Zones" ESP model. This framework includes two ecological barrier zones (the Tianshan and Kunlun–Altyn mountain systems), a protective ring encircling oasis area, and multiple functional subzones that support critical ecosystem services, such as water retention, biodiversity conservation, erosion mitigation, wind protection, and desertification control. While previous ESP models have emphasized landscape structure or habitat quality [51,52], our model innovatively integrates landscape ecological risk assessments with circuit theory-based connectivity mapping, enabling a dual-perspective evaluation of both vulnerability and ecological flow. Furthermore, the delineation of ecological functional zones and emphasis on integrated ecological restoration across mountains, rivers, forests, farmlands, lakes, grasslands, and deserts resonates with holistic landscape management approaches advocated by international assessments [53,54]. Nevertheless, unlike many prior frameworks that treat ecological sensitivity as spatially uniform, our study underscores the spatial heterogeneity of ecological risk as a critical factor in restoration prioritization. This differentiated risk mapping allows decision-makers to allocate limited resources more effectively, an aspect often underdeveloped in conventional ESP planning.

In addition, this research advocates modular and segmental management of ecological elements, informed by InVEST-derived risk surfaces and ecological network topology. This approach complements existing ESP literature by providing a scalable methodology applicable to other ecologically fragile regions—particularly those in Central Asia, North Africa, and the Middle East—where urbanization, water scarcity, and land degradation similarly intersect. Ultimately, by integrating ecological risk evaluation with functional connectivity analysis, this study delivers a replicable, data-driven decision-making tool for reconciling ecological conservation and regional development. The identification of ecological buffer zones and key connectivity nodes provides actionable spatial strategies for biodiversity protection under expanding human influence. These contributions add

empirical and methodological depth to the growing body of literature on sustainable land-use transitions and regional ecological security governance in arid environments.

4.3. Research Deficiencies and Shortcomings

This study acknowledges several limitations. First, the delineation of the study area lacks universal scientific consensus. Accurately assigning resistance values and levels is essential for model validity and significantly impacts ecological network construction. Currently, there are no globally standardized methods for this process. Resistance values derived empirically often overlook the interrelations among land-use types, leading to misrepresentation of resistance characteristics. Thus, defining landscape resistance values should consider research objectives and wildlife distribution patterns. Additionally, determining optimal ecological corridor width remains a major challenge. Corridor width studies are still in their early stages, and existing criteria often vary by study goal, lacking unified justification.

Future research should further optimize the methods for determining landscape resistance and ecological corridor width, so as to enhance the scientific validity and adaptability of the model. At the same time, multi-species migration data and socio-economic factors should be integrated to improve the practicality and accuracy of ecological network construction. Through dynamic simulation and field verification, the effectiveness and sustainability of the ecological security pattern can be more comprehensively assessed.

5. Conclusions

This research employed the IER Index, the InVEST model, and the Landscape Connectivity Index to define the Ecosystem Services Potential of the Tarim Basin in Xinjiang. Employing circuit theory, the spatial dimensions and locations of ecological corridors were determined, and pertinent optimization algorithms were proposed, offering a novel approach for the formulation of ecological security patterns. The primary conclusions are outlined below:

(1) Spatial Differentiation of Ecological Risks. The IER of the Tarim Basin has considerable regional variation. High-risk exposure is prevalent in the central and eastern zones of the desert, branded by severe water scarcity, extensive desertification, and considerable terrain fragmentation.

(2) Identification of Ecological Resources and Corridors. Forty-two ecological sources and ninety-five ecological corridors were found in the oasis regions adjacent to the Tarim Basin. The ecological source regions encompass 244,646.6 km^2, or merely 1.47% of the research area. The sources are distributed across the basin's periphery, with a denser concentration in the northern areas. The biological corridors extend a total of 56,265.5 km, exhibiting limited connectivity between the southern and northern source regions. The study precisely defined the spatial distribution of essential nodes, comprising 48 pinch points and 56 barrier points. The preliminary establishment of the overall ESP of the Tarim Basin was based on these data.

(3) Optimization Strategy for the Ecological Security Framework. A strategic configuration for enhancing the ecological security pattern was presented, comprising "Two Shields, One Ring, and Multiple Zones," tailored to the exact requirements of the research area. This encompasses the Tianshan and Kunlun–Altyn Mountain ranges as the principal ecological barriers, an ecological ring surrounding the oasis of the Tarim Basin, and various ecological service protection zones. The strategy underscores the identification of ecological functional zones to promote the sustainable advancement of the economy and the ecology. Furthermore, protection approaches were offered in accordance with the ecological roles and spatial variability of numerous ecological

components. This study provides crucial insights into biodiversity conservation and sustainable development planning in the region, acting as a reference framework for the formulation of ESPs in arid desert and oasis ecosystems.

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